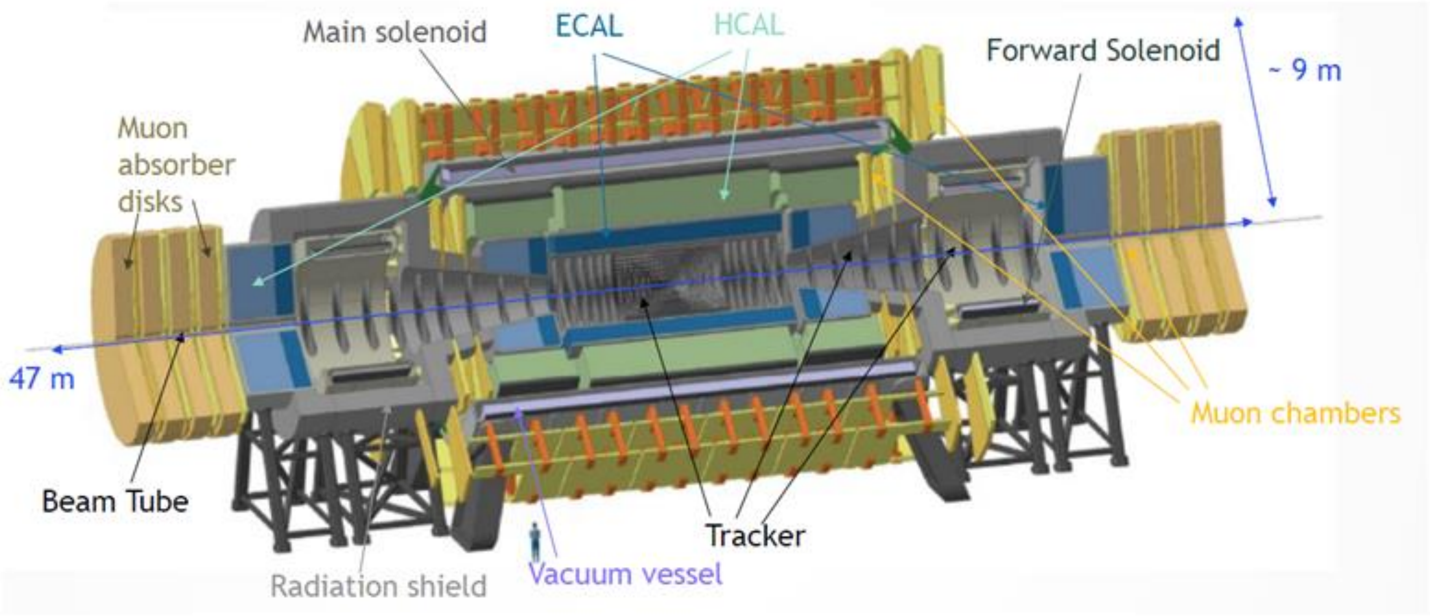
FCC: experimental challenges

Guy Wilkinson
University of Oxford
Israeli ESPPU town-hall meeting
18/12/24

(with thanks to FCC PED colleagues for borrowed material)

What I won't talk about today

Huge detector challenges at FCC-hh, with ~100 TeV operation at 3 x 10^{35} $cm^{-2}s^{-1}$.



- Pile up of 500-1000 – new demands on precision timing;
- Radiation levels 10-30 x worse than HL-LHC (and worse in certain regions);
- Massive computing challenges.

FCC-ee: experimental challenges

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Outline

- General considerations
- Detector challenges

  Vertex detector, tracker, calorimetry….
- Other challenges

  Normalisation, E_{CM} calibration
- Next steps and getting involved

Any unattributed plots, numbers *etc.* (should) be available in Feasibility Study Final Report

General considerations

Differences w.r.t. ILC

Although there are many things in common, there are sufficient key differences that mean we cannot merely take an ILC detector design and re-use it at FCC-ee.

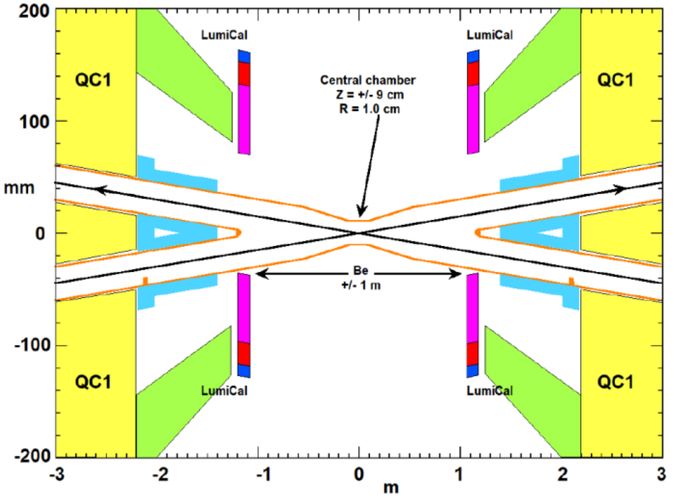
30 mrad crossing angle leads to tightly packed MDI * region and limits B-field to 2T and ~100 mrad acceptance;

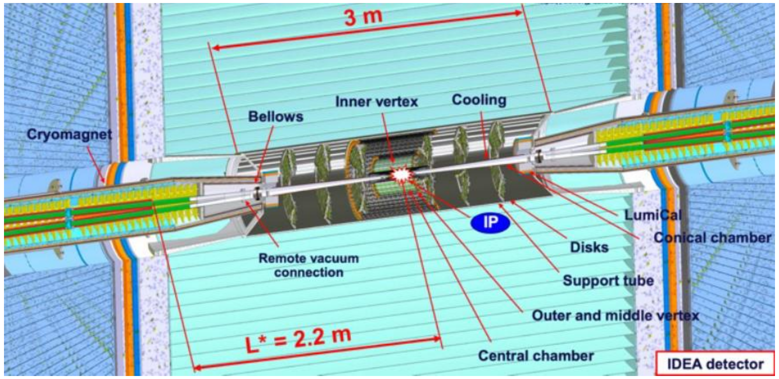
`Continuous’ beams, with spacing down to 20 ns, means no power-pulsing and active cooling required;

Event rates of up to 100 kHz have consequences for detector response, occupancies, backgrounds *etc.*;

Higher luminosities at HZ than ILC demands better systematic control…

…which is an even greater concern at the Z, with lumis of ~10^{36} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$;





Tera-Z run, in particular, opens up many other areas of physics (*e.g.* flavour), each with their own requirements.

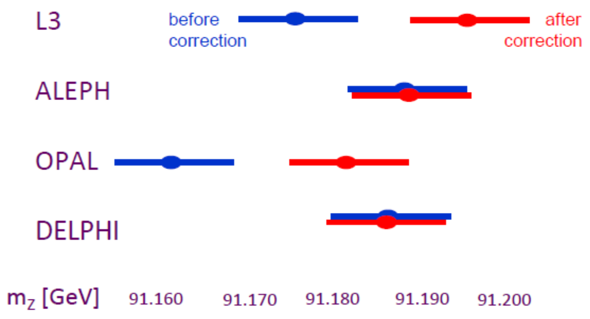
* MDI = machine-detector interface

Four interaction points

Current baseline has four IPs, which has several benefits:

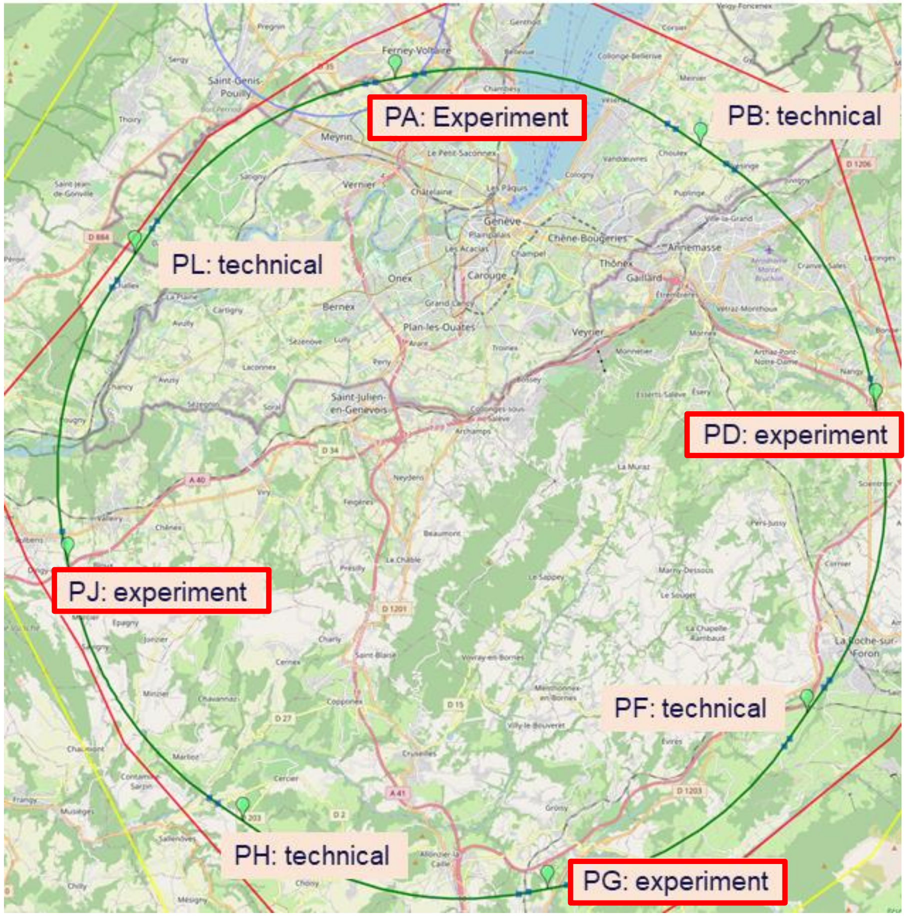
- Increases integrated luminosity by (almost) same factor;
- Provides systematic robustness;

Lessons from LEP – discovery of impact of `RF sawtooth' on Z mass



[PLB 307 (1993) 187]

- Allows for different detector solutions, which will ensure full coverage of the physics goals.

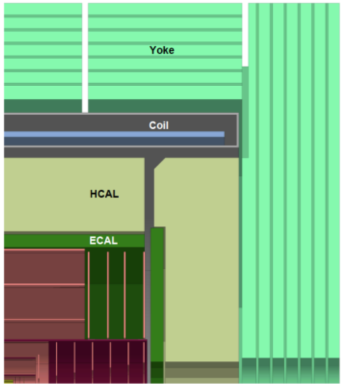


Detector concepts

Four main experimental designs have emerged, which should be viewed as testbeds for evaluating possible detector solutions. Too early for any of these to be regarded as concrete proposals. Collaborations will not form until have project approval.

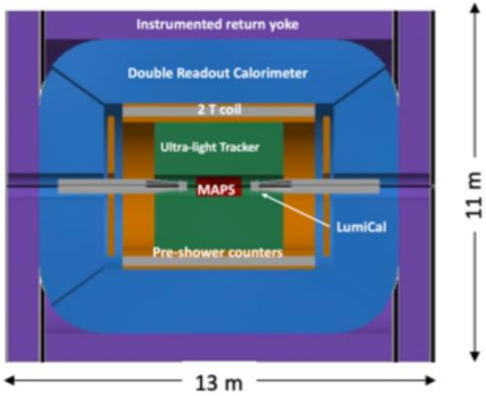
CLD

- Present in CDR;
- Based on CLIC design;
- Full-Si tracker.



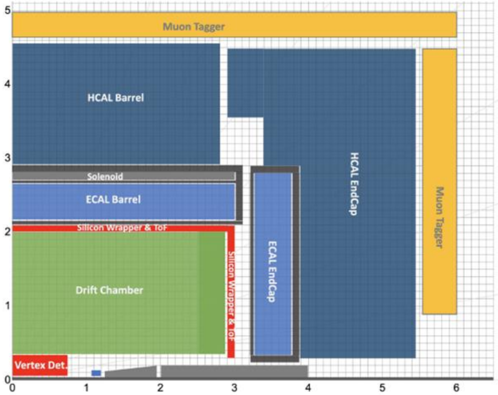
IDEA

- Present in CDR;
- Drift chamber.



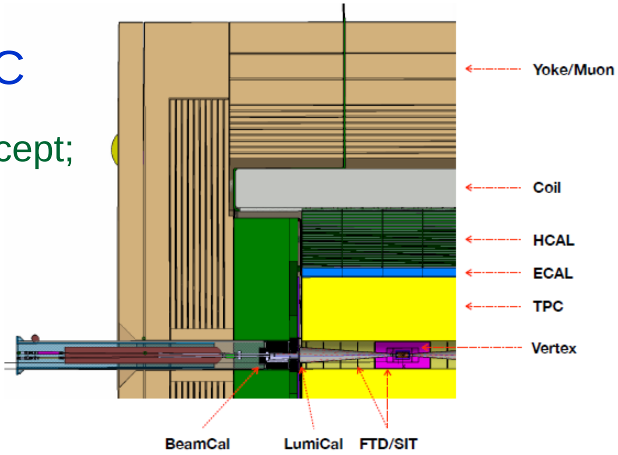
ALLEGRO

- New concept;
- Liquid-noble calorimeter.



ILD for FCC

- Very new concept;
- ILC design →
- TPC.



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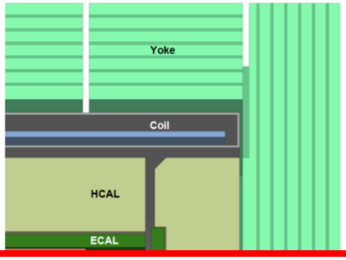

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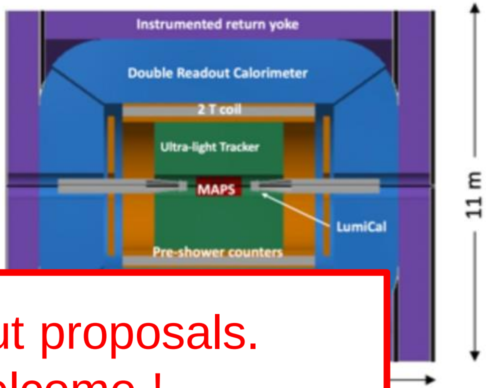

To reiterate, these are ideas, not fully worked-out proposals.
Nothing is fixed, and new ideas are very welcome !

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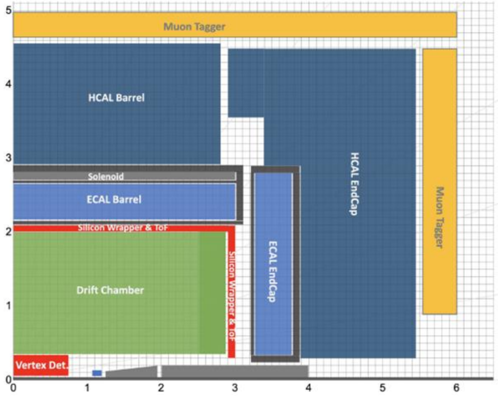

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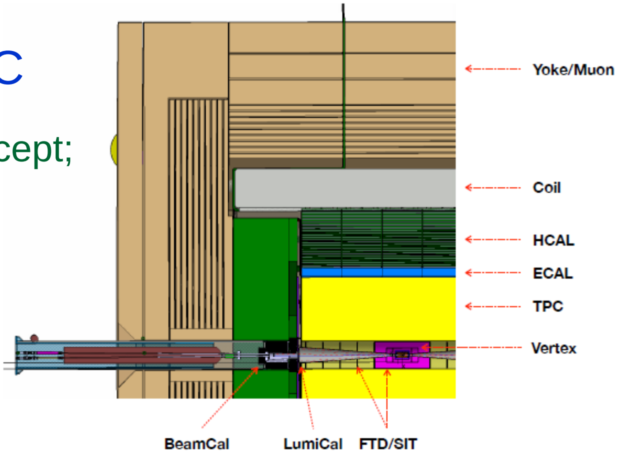

Detector challenges

- Luminometer (see later)
- Vertex detector
- Tracking
- Calorimetry
- Particle identification
- Muon system

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- Particle identification
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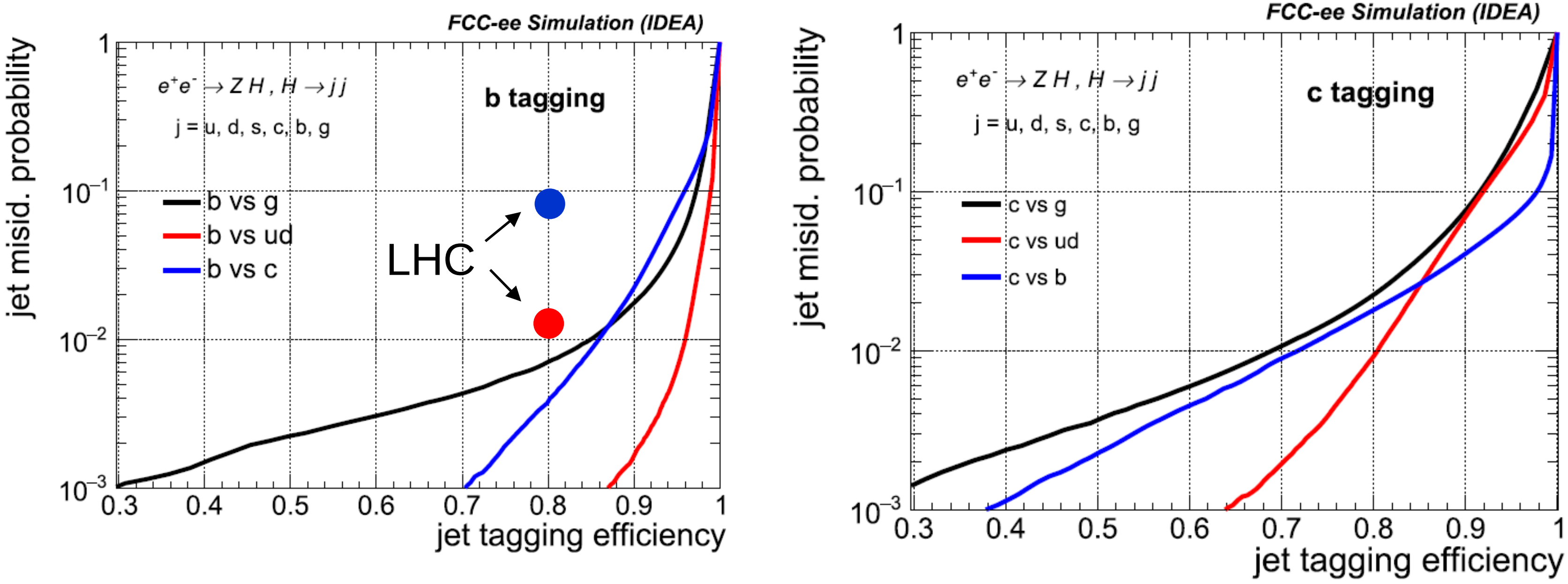
Not covered here because of time constraints. However, some brief remarks:

- Muon system must identify muons with high efficiency and low $\pi\to\mu$ fake rate;
- Also may act as a `tail-catcher' for uncontained hadronic showers;
- Muon momentum resolution entirely driven from tracking system.

Also omitted: trigger, data handling, computing – see Feasibility Study Final Report

Vertex detector – physics drivers

Traditionally, the principal task of vertex detectors at Higgs factories has been in jet-flavour tagging, with initial focus on b & c jets (s & gluon jets of increasing interest). Necessary for Higgs-coupling measurements, but also tagging W and top jets.



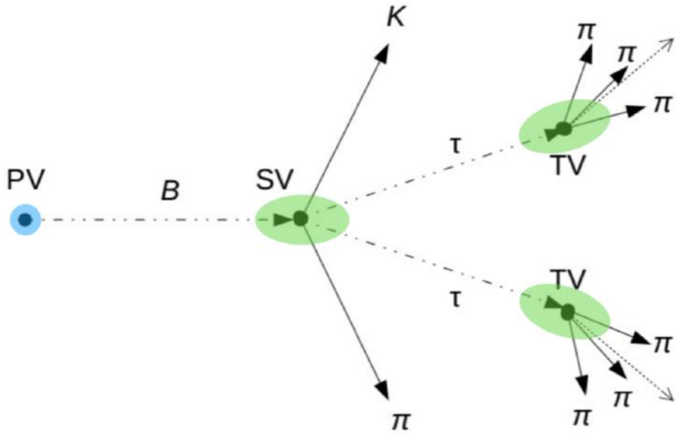
[Bedeschi, Gouskos and Selvaggi, EPJC 82 (2022) 646]

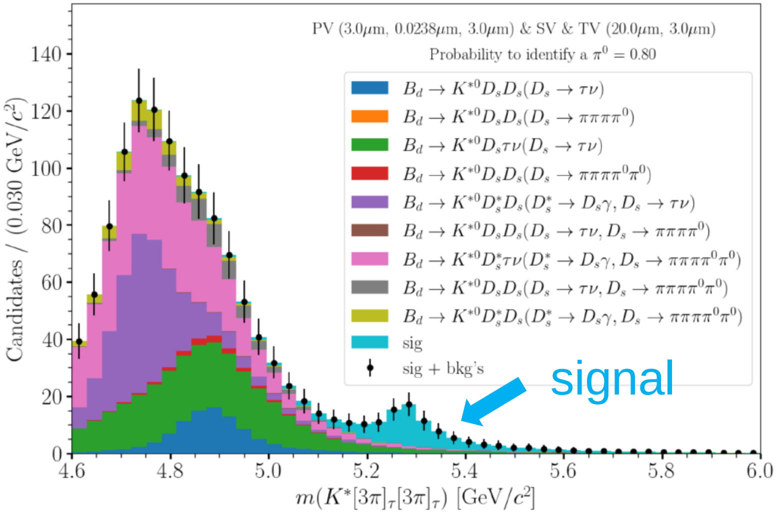
Improvements w.r.t. LHC will be achievable through 1 cm radius, low-mass technologies, & new Machine Learning techniques (here Graph Neural Networks). Particle identification will also play a key role.

Vertex detector – physics drivers

Additional impetus to improving performance comes from heavy-flavour physics, where many channels will require best possible secondary vertex resolution.

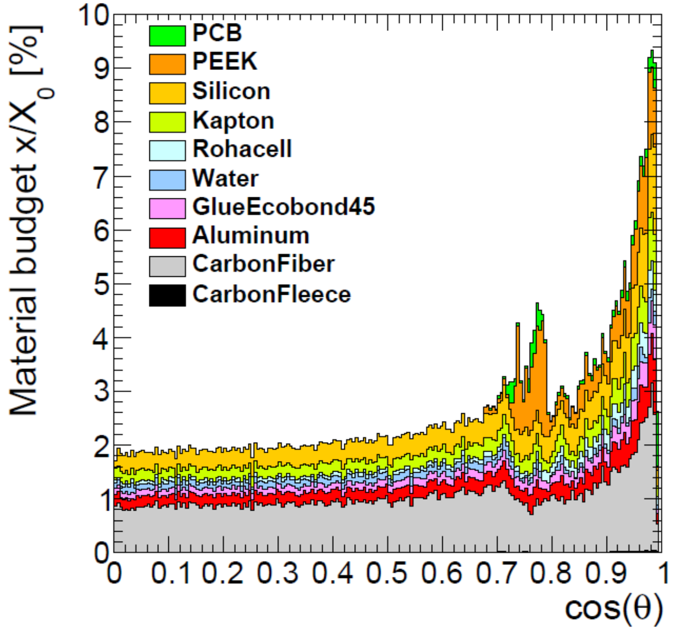
Key example: reconstructing $B \to K^* \tau^+ \tau^-$ decays using secondary (+ tertiary) vertex resolution, and kinematic constraints. Only possible at FCC-ee !





Shown performance assumes 3 μm (20 μm) transverse (longitudinal) resolution.

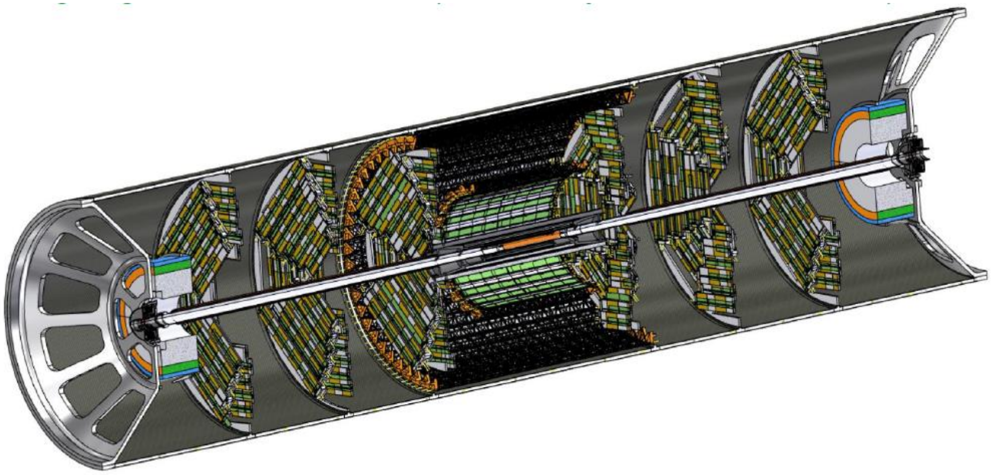
Vertex detector – possible solution (IDEA)

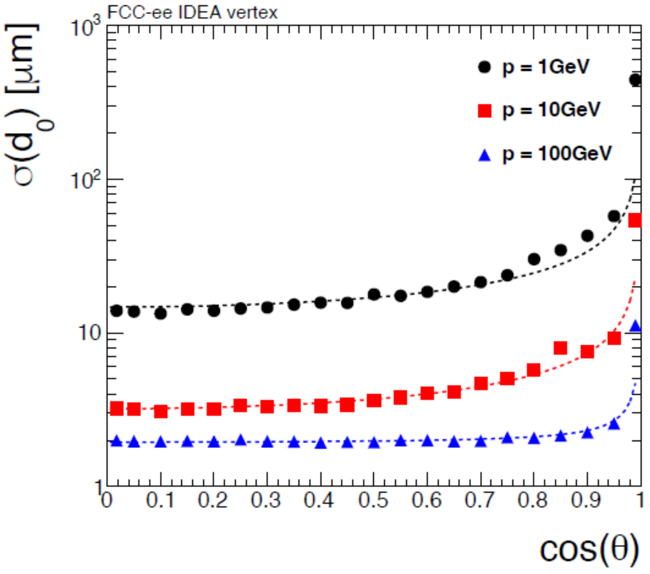


DMAPS technology

Inner three layers, 25 x 25 µm pixels, 0.3% X_0. Supported by beam pipe

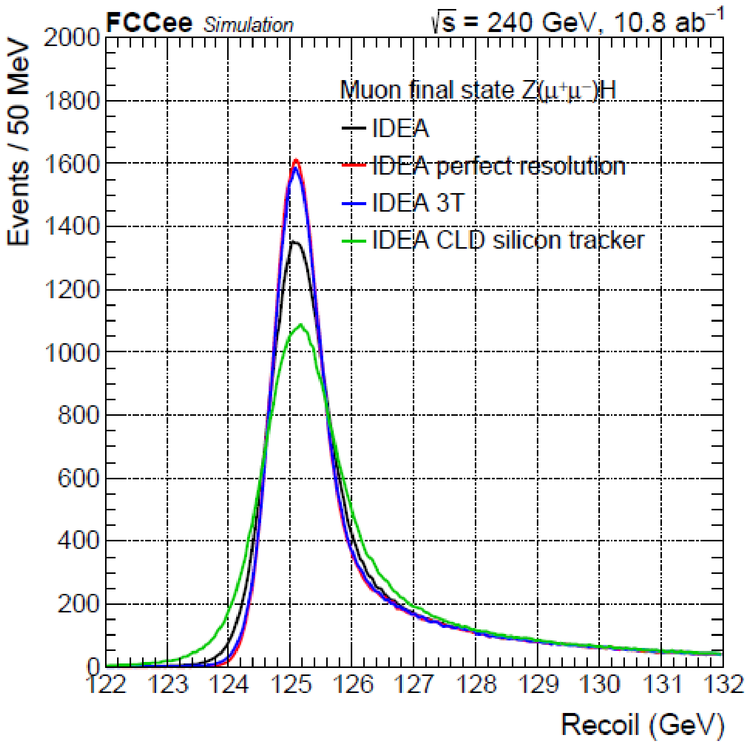
Outer two layers and disk, 1% X_0, mounted on support tube.

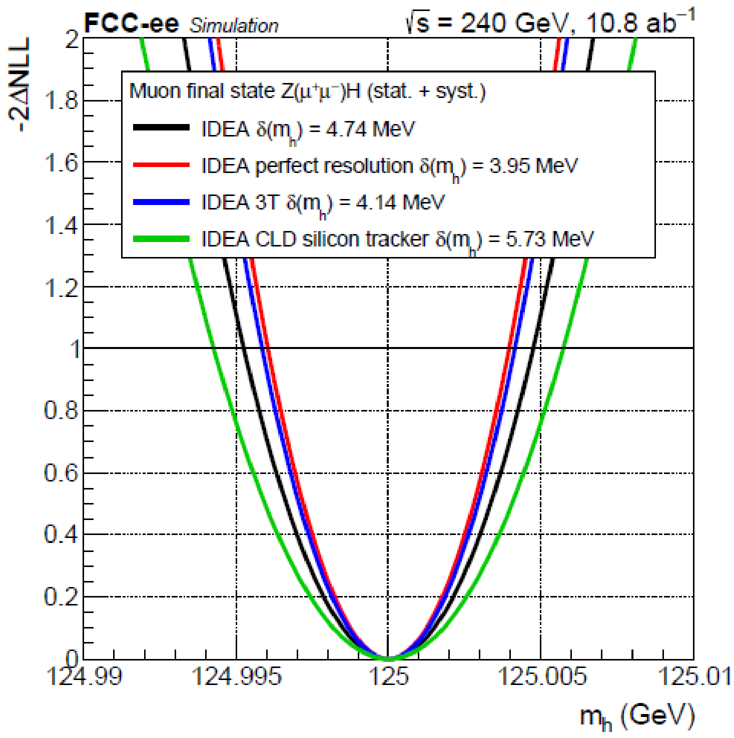




Tracker – physics drivers

Many measurements critically dependent on momentum resolution. Determination of the Higgs mass through recoil in ZH events at 240 GeV a principal test case.

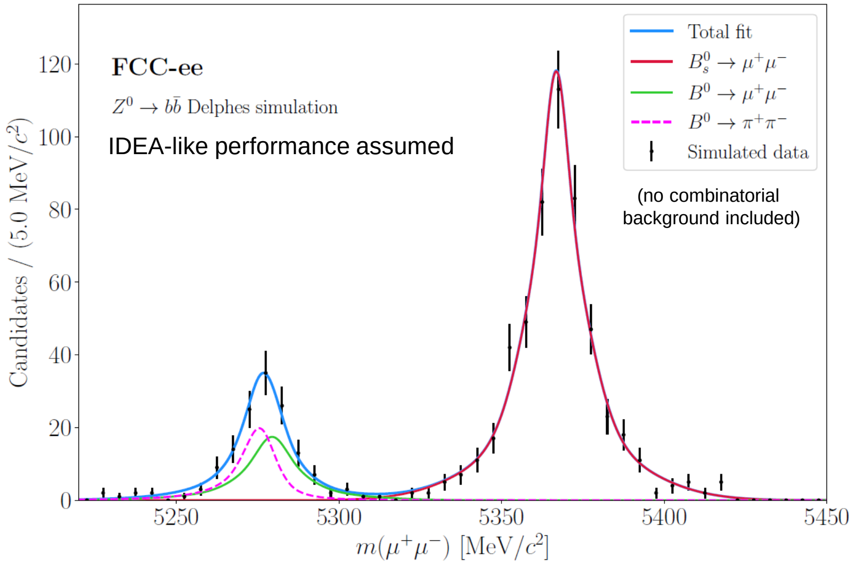




With 10.8 ab^{-1} of data and a perfect detector, the uncertainty on m_H would be 3.95 MeV, limited by 0.185% on √s coming from beamenergy spread. Momentum resolution should not degrade measurement beyond this !

Tracker – physics drivers

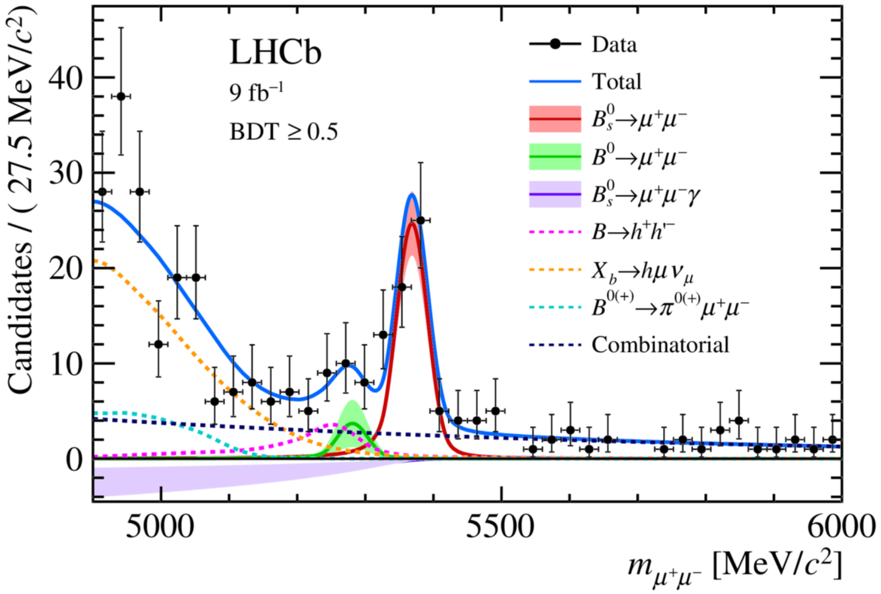
Excellent momentum resolution will have benefits for many other measurements, *e.g.* separation of B_d and B_s mass peaks in flavour physics (below example $B \to \mu\mu$).



IDEA-like performance assumed

(no combinatorial background included)

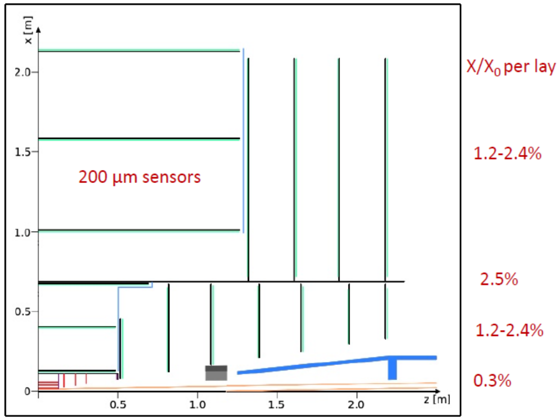
[Monteil & Wilkinson, EPC+ 136 (2021) 837]



[LHCb, PRL 128 (2022) 041801]

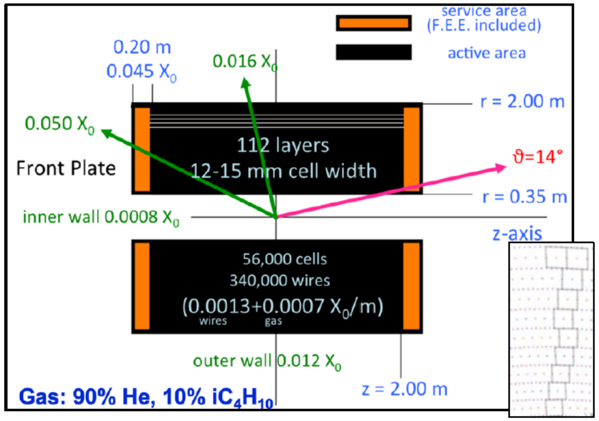
Tracker – possible solutions

CLD – all-silicon tracker



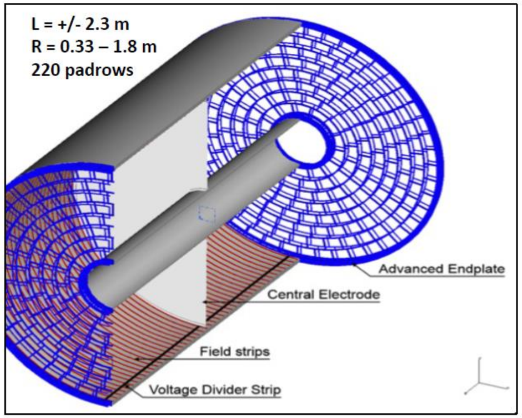
- Precise hit points;
- Proven (LHC) technology;
- Requires cooling;
- Need to reduce material budget.

IDEA – drift chamber



- Very low material budget;
- Proven (KLOE) technology;
- Provides PID through dE/dx (dN/dx);
- Operation to be proved in FCC-ee environment.

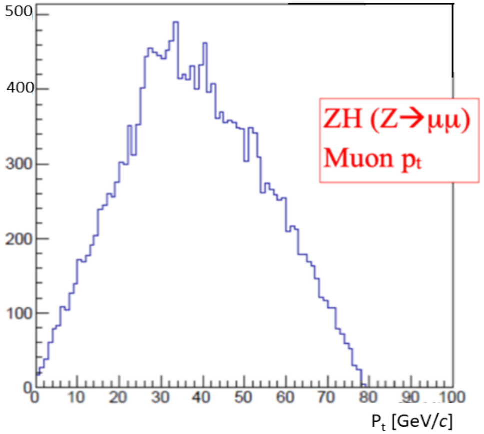
ILD - TPC

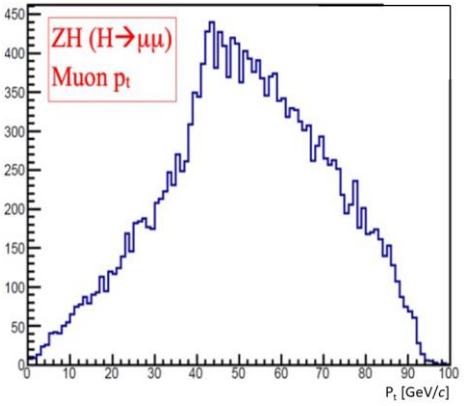


- Low material budget;
- Established technology (LEP & ILC);
- Continuous tracking;
- Provides PID
- Performant at ~100 kHZ FCC-ee event rate ?

Tracker – p_T resolution

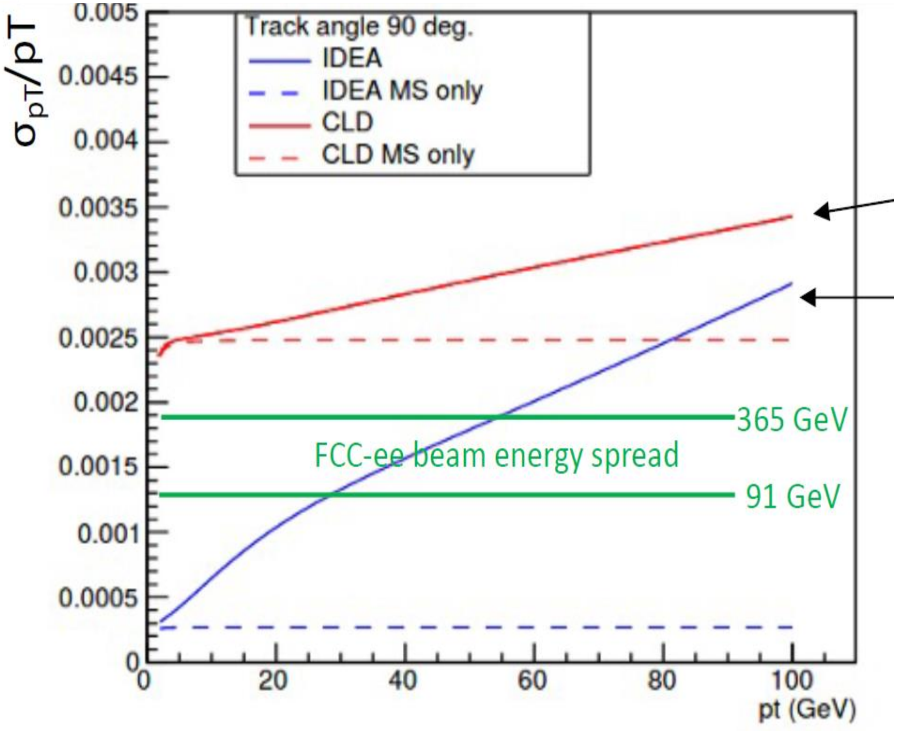
Tracks of interest are of moderate momentum.





Momentum resolution tends to be multiple-scattering dominated → material budget crucial.

$$\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = \underbrace{a}_{\text{resolution}} \oplus \underbrace{\frac{b}{p\sin\theta}}_{\text{mult.scat}}$$



CLD – all-Si tracker with 11% X_0

IDEA – drift chamber (with vertex detector + Si 'wrapper'), with 1.6% X_0

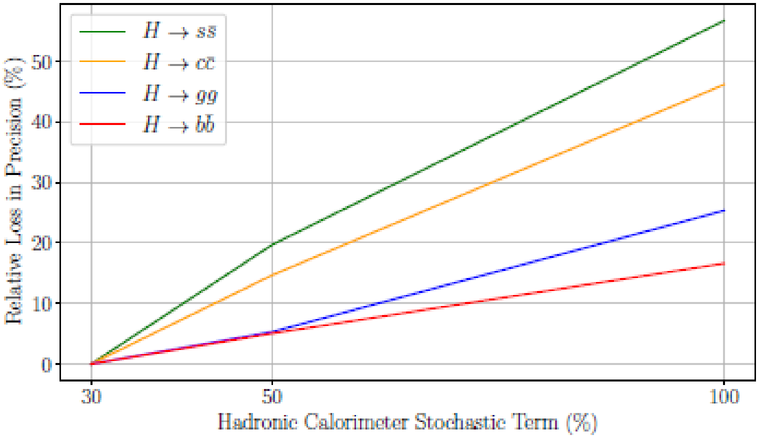
(see later slide)

Calorimetry – physics drivers

Wide breadth of FCC-ee physics programme encompasses many topics where calorimetry is a critical tool, each with rather different physics requirements.

- Jet resolution for Higgs, W and top physics, *e.g.* for flavour tagging, separation of $H\to WW^*$ vs ZZ^* ;
- Study of $e^+e^-\to\nu\nu\gamma$ to measure vector coupling to neutrino;
- Search for ALPs;
- Flavour physics (next slide);
- LFV Z and tau decays
- ….

Degradation in BF precision vs HCAL stochastic term [%]



Broad requirements

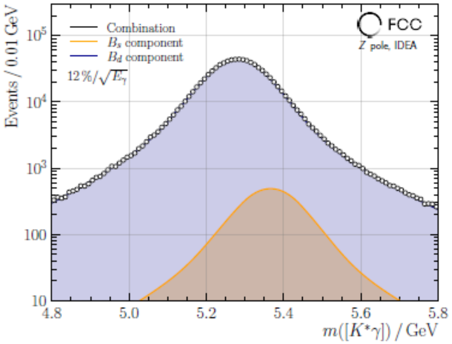
Jet resolution	30% / √ E [GeV]
ECAL resolution for jets	15% / √E [GeV]
ECAL resolution for flavour physics	3%/ √E [GeV]

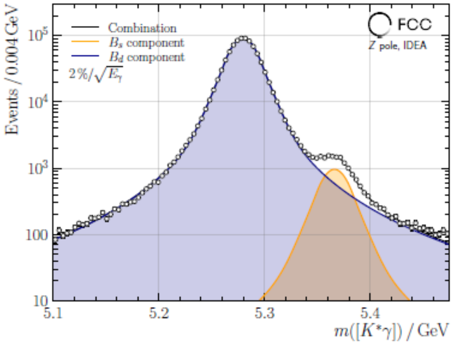
Fine granularity for particle flow and π^0/γ separation

Calorimetry – physics drivers

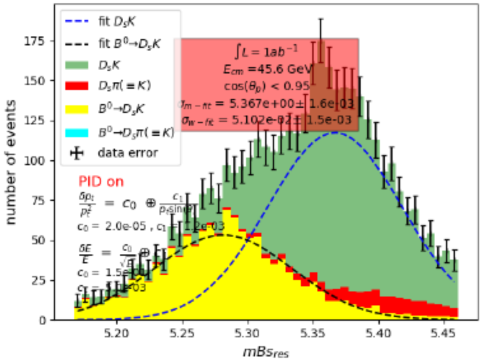
Importance of single γ or π^0 energy resolution for flavour physics.

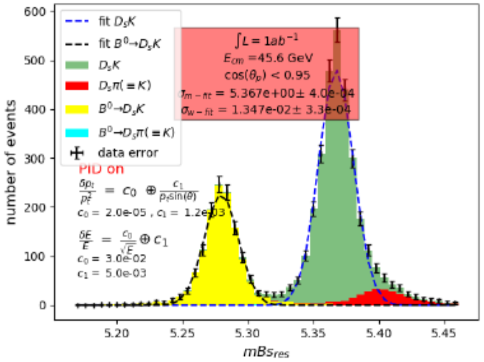
e.g. separating $B_s \rightarrow K\gamma$ and $B_d \rightarrow K\gamma$ with 12% or 2% stochastic term,





or $B_s \rightarrow D_sK$ and $D_s\pi$. With $D_s \rightarrow \pi^0\pi K$, with 15% or 3% stochastic term.





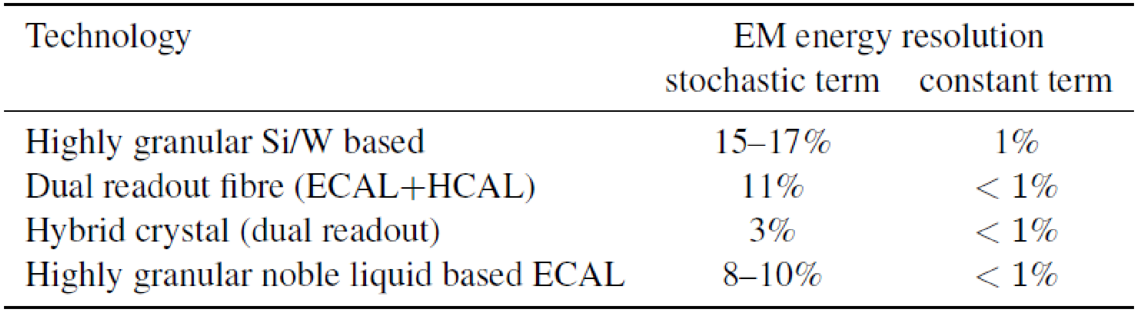
Same lessons apply in tau physics or hadron spectroscopy.

Calorimetry – possible solutions

Several technologies under consideration, driven by ILC R&D / LHC experience:

CLD	Si-W ECAL, with steel/scintillating tile HCAL
IDEA	Dual-readout fibre calorimeter behind solenoid, with crystal ECAL in front
ALLEGRO	High-granularity noble-liquid ECAL, with TileCal HCAL

Indicative performances



Technology	EM energy resolution	
	stochastic term	constant term
Highly granular Si/W based	15–17%	1%
Dual readout fibre (ECAL+HCAL)	11%	< 1%
Hybrid crystal (dual readout)	3%	< 1%
Highly granular noble liquid based ECAL	8–10%	< 1%

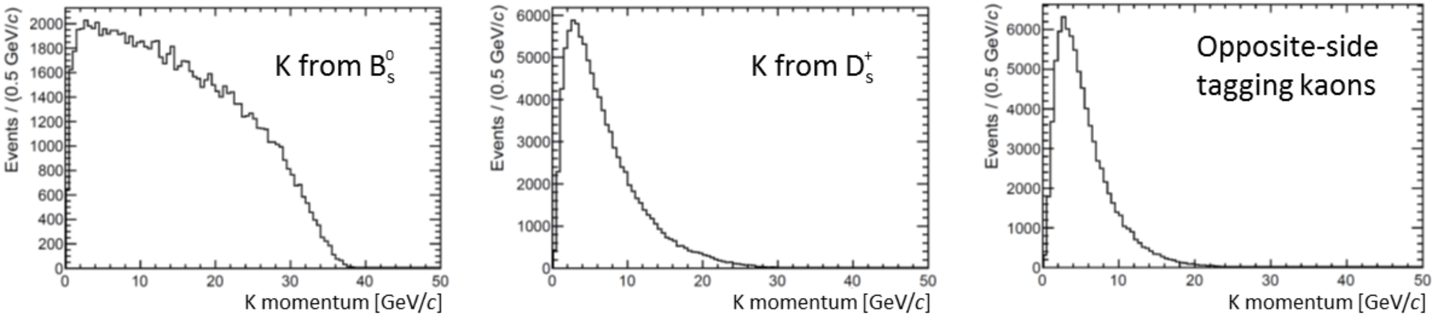
[Aleksa *et al.*, EPJ+ 136 (2021) 1066]

In addition, other novel solutions are being evaluated, *e.g.* GRANITA (see backups).

Particle identification (PID)

PID, in particular π-K separation, traditionally not given high attention in detector planning in e^+e^- `Higgs factory’ studies, but this has changed in recent years:

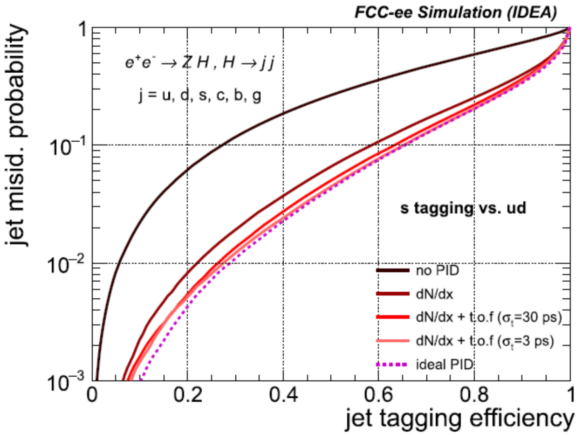
- Tera-Z at FCC-ee offers enormous flavour-physics opportunities. Here, hadron identification is *mandatory*, and over a wide momentum spectrum.



[Wilkinson, EPJ+ 136 (2021) 835]

Kaons in $B_s \rightarrow D_s K$ decays , & `tagging kaons’, require PID 1 < p < 40 GeV/*c*.

- Increasing awareness of the gains that PID can bring in jet-flavour tagging.



[Bedeschi, Gouskos and Selvaggi, EPJC 82 (2022) 646]

Particle identification (PID)

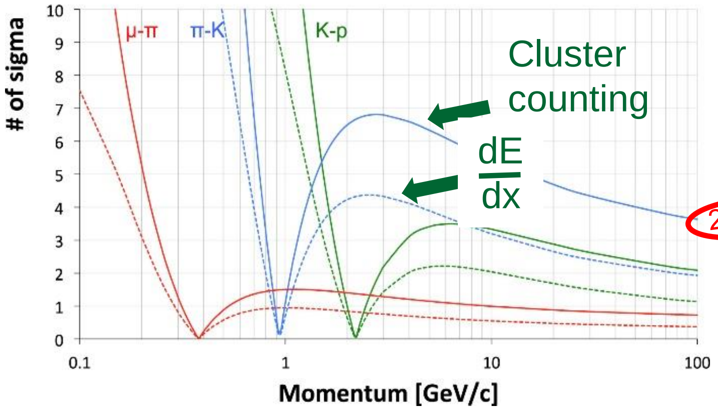
Low momentum PID can be delivered by TOF, or threshold Cherenkov. But other approaches are needed to cover full momentum range. Two interesting possibilities.

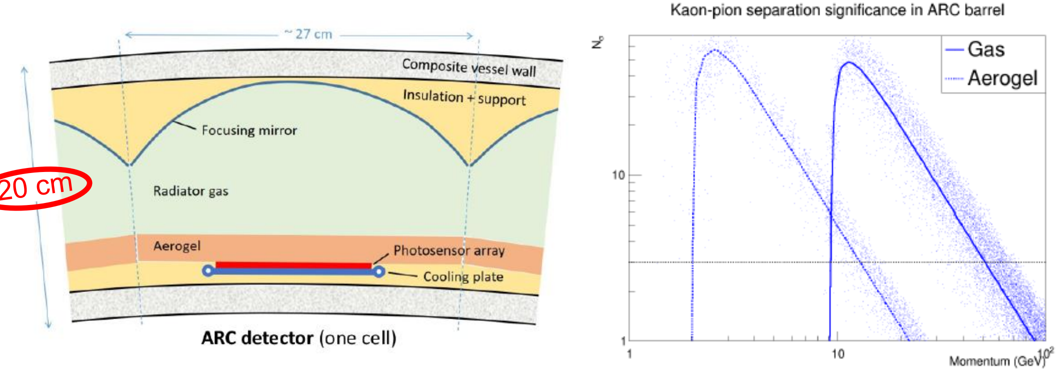
IDEA drift chamber aims to use cluster counting, which goes beyond dE/dx.

Alternatively, equip an experiment with a *compact* RICH system, *e.g.* \`ARC'

Particle separation in IDEA drift chamber
(caution – idealised case, not simulation)

ARC cell and π-K separation
(now included in CLD simulation)





[Chiarello *et al.*, NIM A 936 (2019) 503]

[Forty, Tat, FCC Physics Wkshp Krakow, Jan 2023]

Other challenges

- Normalisation for cross sections
- E_{CM} and E_{CM} related

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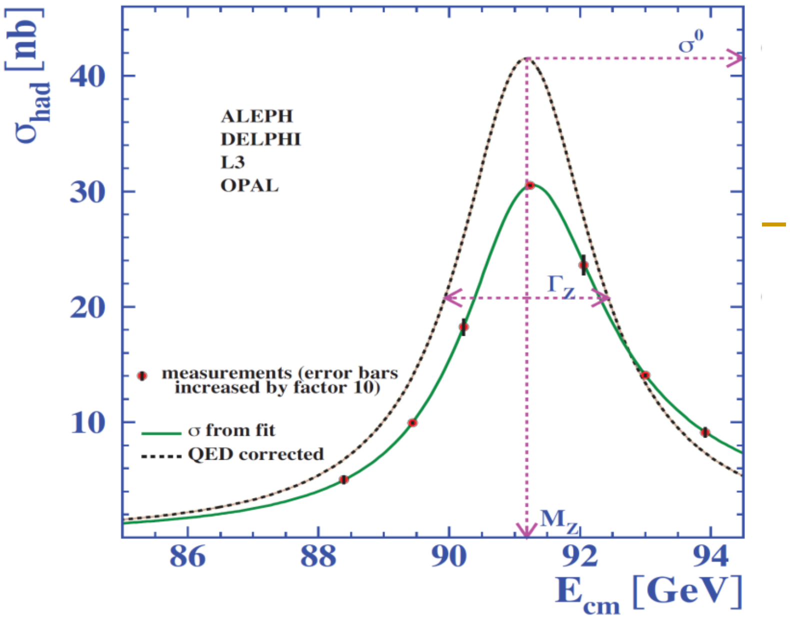

Example: Z resonance parameters (but excellent precision required for other measurements too, *e.g.* m_W)

Other challenges

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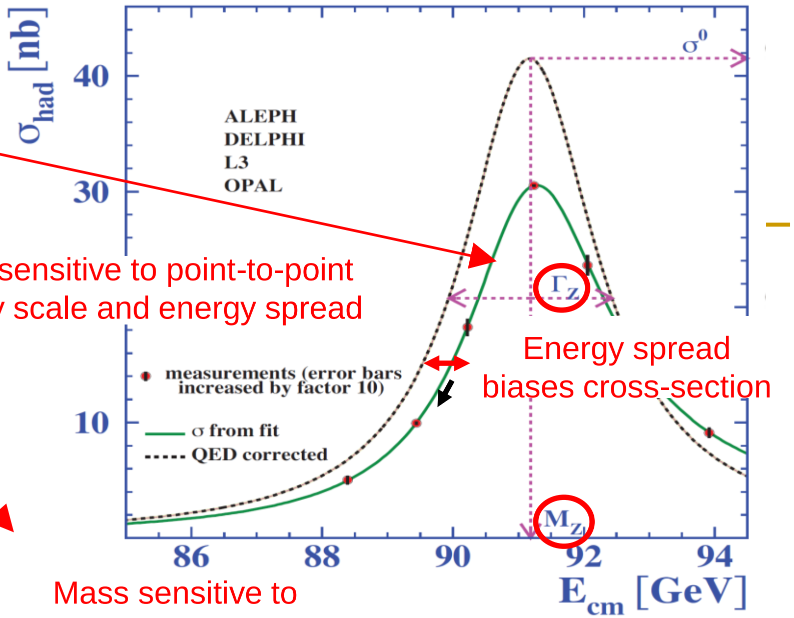
- E_{CM} and E_{CM} related



Width sensitive to point-to-point energy scale and energy spread

Energy spread biases cross-section

Mass sensitive to absolute energy scale

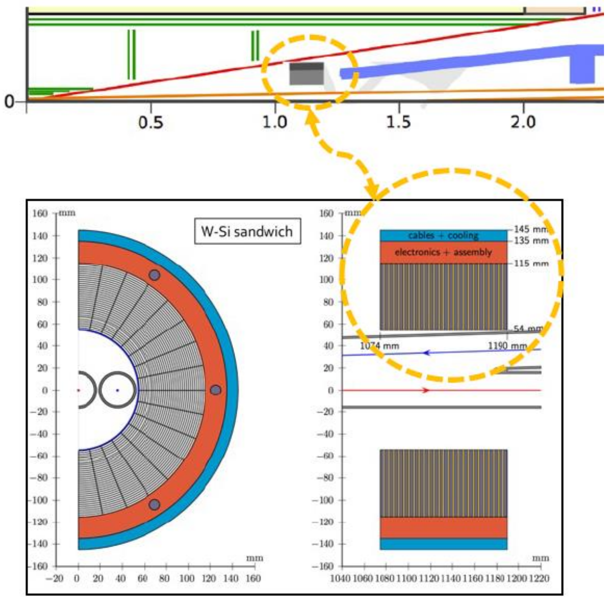
Example: Z resonance parameters (but excellent precision required for other measurements too, *e.g.* m_W)

Normalisation

Ambitious goals:

- Absolute luminosity measurement to 10^{-4} ;
- Relative (`point-to-point') luminosity to 10^{-5} ;

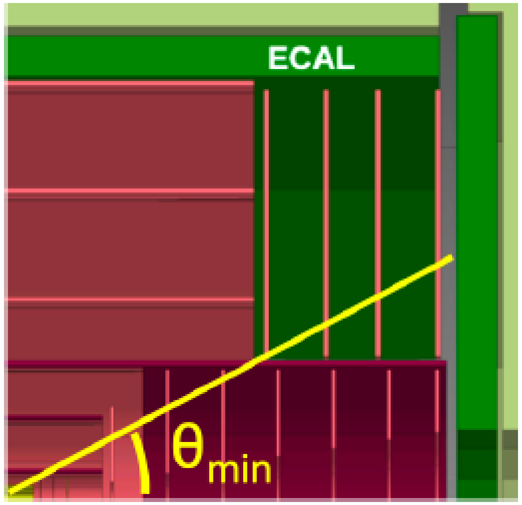
Luminometers for low-angle Bhabhas



- Precision on acceptance ~1 μm;
- Assembly, metrology, alignment challenges;
- Require advances in theory calculations.

Complementary process: large angle $e^+e^- \to \gamma\gamma$ seen in ECAL

- Pure QED – theoretically clean;
- Must control acceptance to 10 μrad;
- Background from $Z \to \pi^0\gamma$?

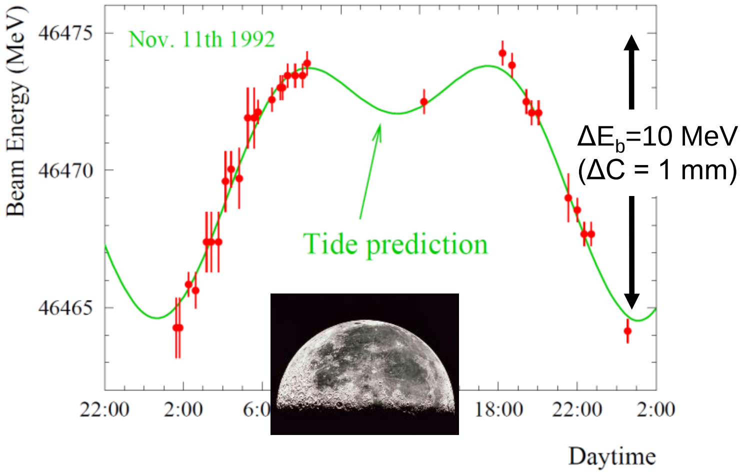


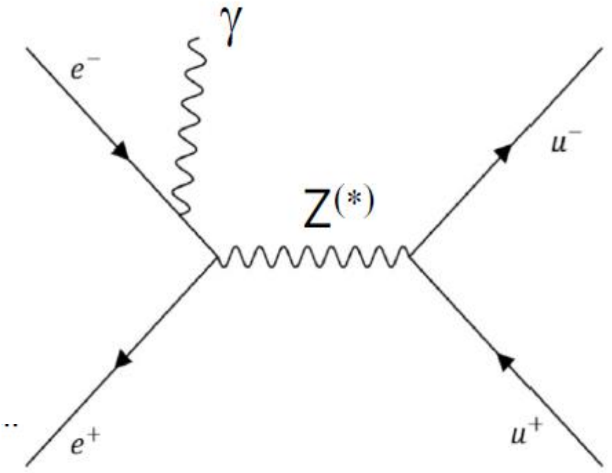
Collision-energy calibration

Absolutely vital for Z mass, Z width, W mass *etc.* Primary tool will be resonant depolarisation of non-colliding pilot bunches to determine instantaneous mean beam energy. Corrections are then required to translate to E_{CM} at each IP.

Lesson from LEP: this is not just the responsibility of the machine, but should be a joint effort between the machine and the experiments.

e.g. discovery of earth-tide effects





Indeed, experiments will be the principal source of information on quantities such as

- crossing angle,
- longitudinal boost,
- spread on E_{CM},
- change in E_{CM} between energy points,

that can be determined directly from the 10^6 dimuon events / *s*, expected at the Z.

Next steps and getting involved

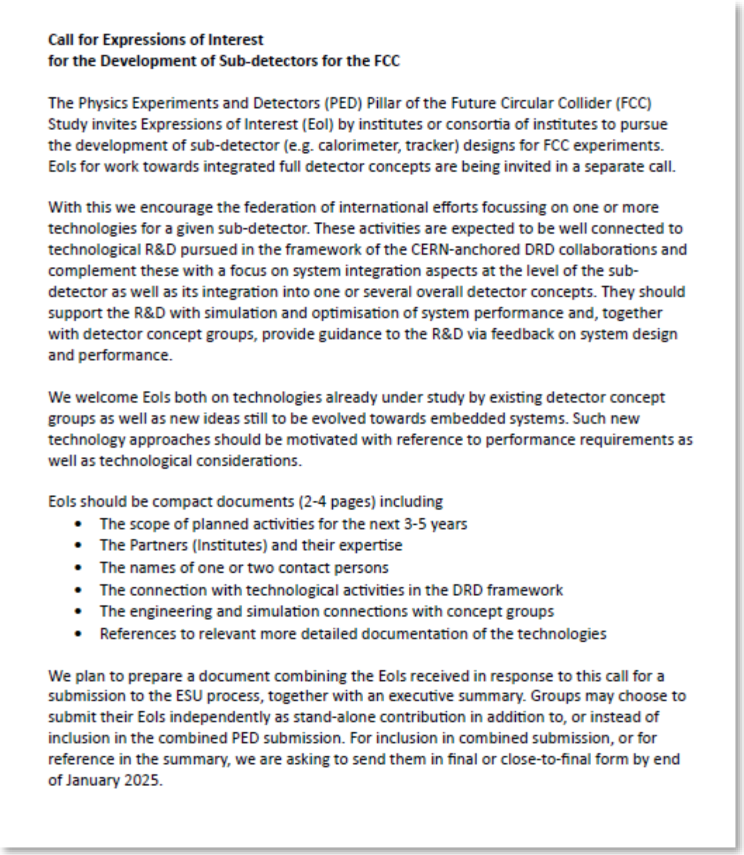
Next steps and getting involved

The Final Report of the Feasibility Study is almost finished, but the work in the pre-TDR phase will begin in earnest early next year. Newcomers welcome !

On detector concepts, there is a large overlap with the DRD Collaborations for R&D, recently formed at CERN.

In addition, we are encouraging small groups to form, focused on specific sub-detector solutions. See recent call for EoIs (more info in backups). These will be discussed in the Physics Workshop in January at CERN.

For questions about becoming involved in any area, please contact the relevant coordinator/convener (see next slide).



Call for Expressions of Interest
for the Development of Sub-detectors for the FCC

The Physics Experiments and Detectors (PED) Pillar of the Future Circular Collider (FCC) Study invites Expressions of Interest (EoI) by institutes or consortia of institutes to pursue the development of sub-detector (e.g. calorimeter, tracker) designs for FCC experiments. EoIs for work towards integrated full detector concepts are being invited in a separate call.

With this we encourage the federation of international efforts focussing on one or more technologies for a given sub-detector. These activities are expected to be well connected to technological R&D pursued in the framework of the CERN-anchored DRD collaborations and complement these with a focus on system integration aspects at the level of the sub-detector as well as its integration into one or several overall detector concepts. They should support the R&D with simulation and optimisation of system performance and, together with detector concept groups, provide guidance to the R&D via feedback on system design and performance.

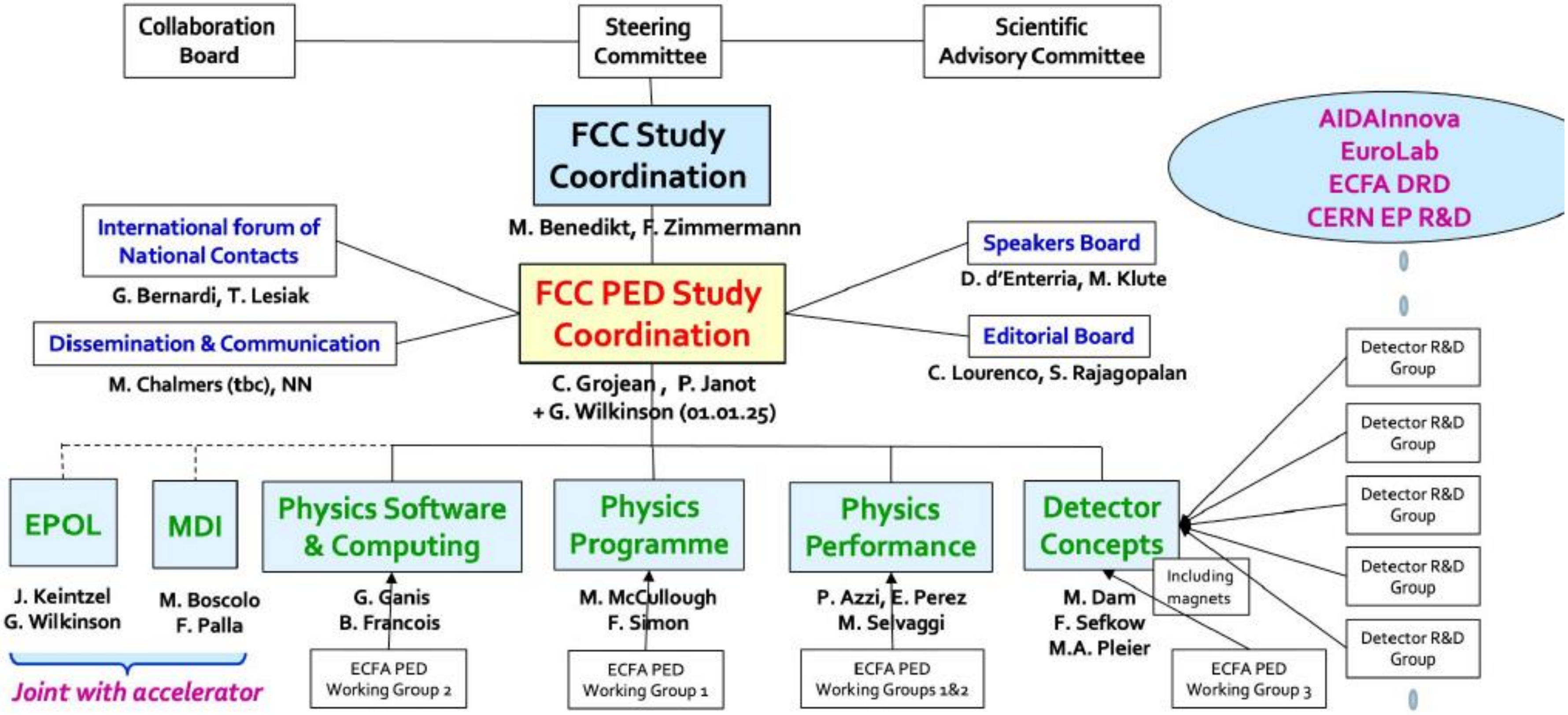
We welcome EoIs both on technologies already under study by existing detector concept groups as well as new ideas still to be evolved towards embedded systems. Such new technology approaches should be motivated with reference to performance requirements as well as technological considerations.

EoIs should be compact documents (2-4 pages) including

- The scope of planned activities for the next 3-5 years
- The Partners (Institutes) and their expertise
- The names of one or two contact persons
- The connection with technological activities in the DRD framework
- The engineering and simulation connections with concept groups
- References to relevant more detailed documentation of the technologies

We plan to prepare a document combining the EoIs received in response to this call for a submission to the ESU process, together with an executive summary. Groups may choose to submit their EoIs independently as stand-alone contribution in addition to, or instead of inclusion in the combined PED submission. For inclusion in combined submission, or for reference in the summary, we are asking to send them in final or close-to-final form by end of January 2025.

FCC Physics, Experiments and Detectors (PED) current organisation



Collaboration Board

Steering Committee

Scientific Advisory Committee

FCC Study Coordination

M. Benedikt, F. Zimmermann

AIDAInnova
EuroLab
ECFA DRD
CERN EP R&D

International forum of National Contacts

G. Bernardi, T. Lesiak

Dissemination & Communication

M. Chalmers (tbc), NN

FCC PED Study Coordination

C. Grojean , P. Janot
+ G. Wilkinson (01.01.25)

Speakers Board

D. d'Enterria, M. Klute

Editorial Board

C. Lourenco, S. Rajagopalan

EPOL

J. Keintzel
G. Wilkinson

MDI

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F. Palla

Joint with accelerator

Physics Software & Computing

G. Ganis
B. Francois

ECFA PED Working Group 2

Physics Programme

M. McCullough
F. Simon

ECFA PED Working Group 1

Physics Performance

P. Azzi, E. Perez
M. Selvaggi

ECFA PED Working Groups 1&2

Detector Concepts

Including magnets

M. Dam
F. Sefkow
M.A. Pleier

ECFA PED Working Group 3

Detector R&D Group

Detector R&D Group

Detector R&D Group

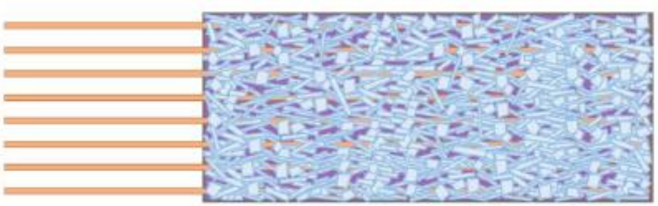
Detector R&D Group

Detector R&D Group

Backups

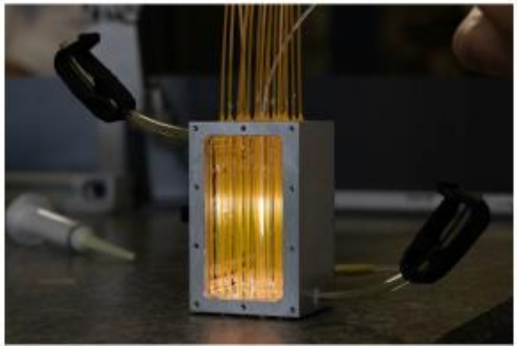
Novel calorimetry – GRANITA (next generation shashlik)

Use grains of inorganic scintillating crystal, read out by wavelength shifting fibres.



Excellent expected EM resolution: 1% / √E [GeV]

- Using BGO or ZnWO4 crystals;
- First small 16-channel prototype evaluated with cosmics.



Main R&D topics:

- Testbeam evaluation (analysis ongoing);
- R&D on crystal grains;
- Aim for larger prototype.

[recent talks: link 1 & link 2]

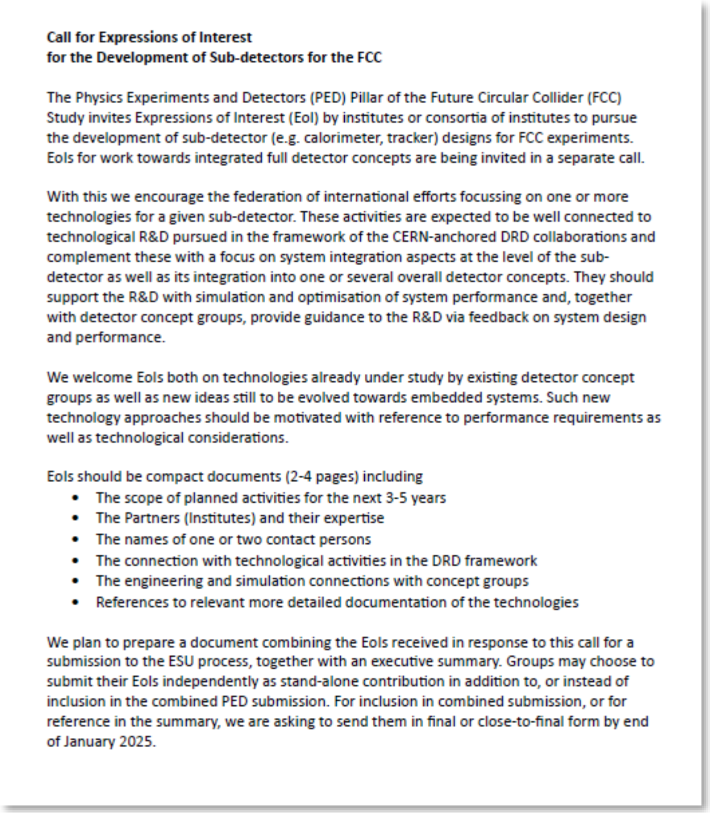
Detector concepts EoI

Current list of EoIs – googledoc

Current EoIs, grouped by area – googledoc

Submission form – googledoc

First discussion planned for Friday of the 2025 FCC Physics Workshop.



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Any questions, contact the FCC Detector Concept Conveners (Mogens Dam, Marc-Andre Pleier and Felix Sefkow).